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SUSY SEARCHES AT THE TEVATRON COLLIDER

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Recent results of the SUSY searches at a center-of-mass energy of 1.96 TeV in RunII of the Tevatron collider experiments CDF and DØ are presented. Analyses are based on up to $185\,pb^{-1}$ of data collected from June 2002 until September 2003. Direct searches of charginos, neutralinos, squarks and gluinos in mSUGRA and in mGMSB models are complemented by an indirect SUSY signal search in rare $B \to \mu\mu$ decays. Model dependent mass limits set here surpass those of RunI.

1 Introduction

Standard Model (SM) of particles interactions has been very successful in describing a variety of experimental data in the vast energy range. Nevertheless there are still a lot of unanswered questions as e.g. the mechanism of the electroweak symmetry breaking, explanation of particles masses or mixing patterns, replication of generations etc. Also the technical or aesthetical reasoning, see e.g. naturalness problem or the large number of free parameters, support the idea that we need a theory behind the SM [1].

Well motivated extension of the SM is the Supersymmetry (SUSY) theory, which relates fermionic and bosonic degrees of freedom via the supersymmetric transormations [2]. From the experimental fact that no SUSY particles has been observed so far, we conclude that SUSY must be broken, and that sparticles must be heavier than their SM partners. The lower range of sparticle masses can be within the reach of the currently most powerfull high energy collider, the Tevatron $p\bar{p}$ collider. Both Tevatron experiments CDF and DØ are performing searches in a large number of different channels, within different SUSY scenarios.

The integrated luminosity used in some of the searches presented here is by factor 2 higher than the one collected in RunI. All presented analyses assume R-parity conservation. This leads to the expected production of SUSY particles in pairs and to the existence of weakly interacting, stable, lightest SUSY particle (LSP). LSP escapes the detection and is the source of canonical SUSY signature - large missing $\not\!\!E_T$. SUSY could manifest itself also indirectly, e.g. via loops in rare B-meson decays ($B \to \mu\mu$).

2 DØ Search for Charginos and Neutralinos in Trileptons Signature

For the case that squarks and gluinos are too heavy to be produced at Tevatron, the dominant SUSY process would be electroweak associated chargino-neutralino production [3]. In the mSUGRA model this process can lead to the signatures with 3 isolated leptons and a large missing E_T. This channel is considered to be the "gold-plated" one. But there are also caveats - the cross section of this electroweak process is not very high [4] and the leptons in the final state can be rather soft. The search for this channel is performed in 3 different signatures, namely with $2e + \ell$, $e + \mu + \ell$ and 2 like-sign μ. Main background is coming from Υ, W, Z production. Events with pairs of opposite sign, same flavour leptons with invariant mass $M_{\ell^+\ell^-} < 15\ GeV/c^2$ resp. in the range $70 - 110\ GeV/c^2$ or back-to-back in the azimuthal angle $\Delta\phi(\ell^-\ell^+)$ are rejected.

Potential $b\bar{b}/c\bar{c}$ QCD background estimated from the data is effectively suppressed by a cut on the missing E_T and lepton isolation. In each analysis isolated leptons with matched high quality tracks and cuts on p_T are asked for (Tab. 1).

Channel	$mE_T(GeV)$	$p_{T_{\ell_1}}(GeV)$	$p_{T_{\ell_2}}(GeV)$	$\lvert\Delta\phi(\ell^-\ell^+)\rvert$
$2e+\ell$	> 20	> 12	> 8	< 2.8
$e+\mu+\ell$	> 15	$> 12\ (e)$	$> 8\ (\mu)$	< 2.5
$2LS\mu$	> 15	> 11	> 5	< 2.7

Table 1. Basic selection cuts for different signatures with isolated leptons.

In the signature $2e + \ell$ the events with high energy jet $E_T > 80\ GeV$ are vetoed and the third lepton is looked for as a high quality isolated track with $p_T > 3\,GeV$. Final cut makes use of the correlation between p_T of the third lepton and the event missing E_T, $mE_T \times p_T > 250\ GeV^2$.

In order to reject events with muons ($e + \mu + \ell$ signature) which have their origin in jets, also the isolation criterium in the calorimeter is applied. Events with 1 jet are vetoed if jet $E_T > 60\ GeV$, and events with at least 2 jets, if $E_{T_1} > 40\ GeV$ and $E_{T_2} > 30\ GeV$.

The idea behind the search for events with 2 like-sign μ is to profit from the signature unusual for the SM background and at the same time to profit from the larger acceptance asking for only 2 instead of 3 leptons. Cut on the like-sign dimuon mass $M_{\mu\mu} < 80\ GeV/c^2$ rejects events with wrongly estimated μ charge.

2.1 Trileptons - Summary

Results for the searches in all 3 signatures are summarised in Tab. 2. In order to reach higher sensitivity, the results are in the end combined using the likelihood ratio method [5]. Overlapping events were assigned to the channel with the highest S/B ratio. E.g. the overlap between $e + \mu + \ell$ and $e + e + \ell$ channels is 15%, for the like sign dimuon channel the overlaps are negligible. The highest contribution to the correlated errors is coming from the luminosity measurement.

Signal Monte Carlo has been generated for universal gaugino and scalar masses at the GUT scale in the range $m_{1/2} = (165, 185)$ resp. $m_0 = (72, 88)$. Values of the other mSUGRA parameters were set to $tan\beta = 3$, $A_0 = 0$, and $\mu > 0$. Basic mass relation $m_{\chi_1^\pm} \simeq m_{\chi_2^0} \simeq 2m_{\chi_1^0}$ is valid for a large part of the mSUGRA parameter space. Significant improvement with respect to the RunI results is achieved, although the sensitivity is still insufficient to reach the mSUGRA prediction (Fig. 1). Nevertheless, this result can help to constrain more generic SUSY models with compatible mass hierarchies.

Channel	$\int Ldt(pb^{-1})$	$\#Events$	
		Expect. Bgr	Found
$2e+\ell$	175	0.3+0.4-0.3	1
$e+\mu+\ell$	158	0.54 ± 0.24	0
$2LS\mu$	147	0.13 ± 0.04	1

Table 2. Summary for the searches in 3ℓ signatures.

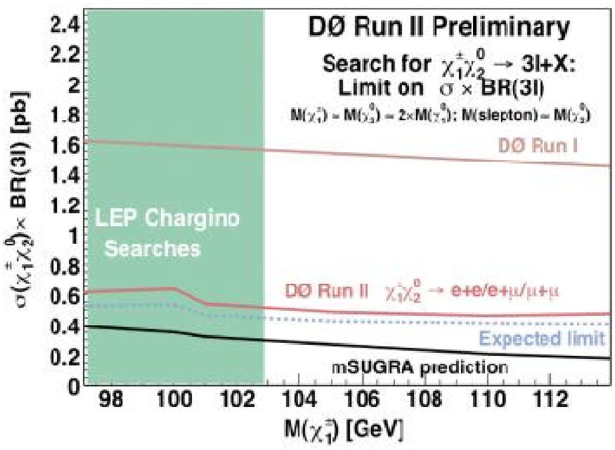

Figure 1. DØ combined results for 3-lepton searches in the associated chargino-neutralino production.

3 DØ Search for Squarks and Gluinos

If the masses of squarks and gluinos are light enough, their production at Tevatron would dominate. The decay chain depends on the assumed mass relations. Most general signature would be *n-jets* with *m-leptons* and a *large missing* E_T.

In the following analysis of DØ data the squarks are assumed to be lighter than gluinos. This mass hierarchy is encountered in mSUGRA model by requesting $m_0 \ll m_{1/2}$. The mSUGRA parameters were chosen at the boundary of the Run I exlusion region: $tan\beta = 3$, $A_0 = 0$, $\mu < 0$, $m_0 = 25\ GeV/c^2$, $m_{1/2} = (100, 140)$ in $5\ GeV/c^2$ steps. In this case the squarks pair production and their 2-body decays into quark and neutralino would dominate, leading to the experimental signature of 2 acoplanar jets and a large missing E_T ($p\bar{p} \to \tilde{q}\bar{\tilde{q}} \to qq^{'}\chi_1^0\chi_1^0$).

This analysis uses only $85\,pb^{-1}$ of data because of the lack of an efficient trigger for this channel before April 2003.

Main background from QCD processes and a $W/Z + jets$ production is studied from the data resp. from Monte Carlo events generated with ALPGEN interfaced to PYTHIA. Signal selection is looking for at least 2 high energy jets $p_{Tjet1} > 60\ GeV$ resp. $p_{Tjet2} > 50\ GeV$. Leading jet should be in the central calorimeter part $|\eta_{det1}| < 0.8$ and an acoplanarity cut between the 2 leading jets is $\Delta\Phi < 165°$. Longitudinal z position of the vertex is restricted to $|z| < 60\ cm$ in order to ensure correct primary vertex reconstruction.

To reduce the remaining QCD events with jets mismeasurements a $CPF > 0.05$ cut is used. Charged Particle Fraction is a fraction of jet energy as measured by the central tracker from the charged particles in the calorimeter jet cone. The CPF value is expected to be close to zero either if wrong primary vertex was selected or if the jet is a fake one.

To suppress electroweak W/Z+jets production a veto on electromagnetic objects and muons is used. Cut on missing $E_T > 60\ GeV$ and topological cut on the angular separation between missing E_T and jets $30° < \Delta\phi(mE_T, jet) < 165°$ kills the QCD background (Fig.2), which has only moderate missing E_T and is correlated with the jets. Final cuts $H_T = \sum_{i=1}^{njet} E_T > 275\ GeV$ and $mE_T > 175\ GeV$ were optimized for the gaugino mass $m_{1/2} = 130\ GeV/c^2$. From the observed 4 events and expected background 2.7 ± 0.95 events the obtained mass limits $m_{\tilde{q}} > 292\ GeV/c^2$ and $m_{\tilde{g}} > 333\ GeV/c^2$ are better than previous Run I limits [6].

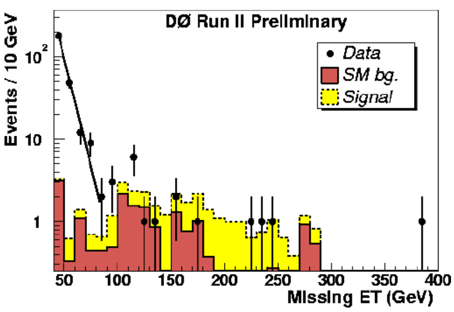

Figure 2. Missing E_T distribution before the final cut $mE_T > 175\ GeV$ in the gluinos, squarks DØ search. Exponential fit shows quickly falling QCD background.

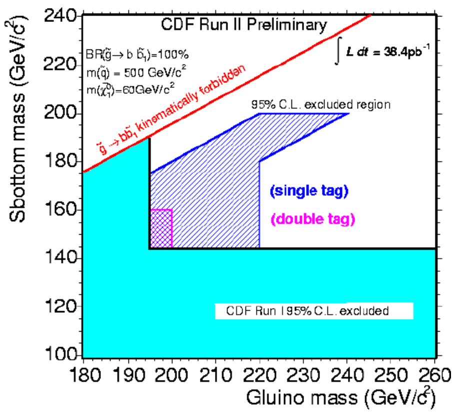

Figure 3. CDF exclusion plot in the gluino-sbottom quark mass plane.

4 CDF Sbottom Search

At large $tan\beta$ due to a large left-right mixing the third generation of squarks could be very light $m_{\tilde{b}_1} \ll m_{\tilde{q}}$. Sbottom pairs could be produced directly or via the dominant gluinos pair production. In the latter case a spectacular signature of 4 b-jets accompanied by a large missing E_T would be observable in the final state.

In the preselection phase events with at least 3 jets with $E_T > 15\ GeV$ and in the rapidity range $|\eta| < 2.0$ and $mE_T > 35\ GeV$ are selected. Electroweak background $W/Z + jet$ is strongly reduced by leptons veto and the QCD background $(b\bar{b}, t\bar{t})$ by topological cuts on the correlations between jets and missing E_T. Final signal searching cuts are missing $E_T > 50\ GeV$ and 2 independent analyses are asking for exclusive single or inclusive double b-tagged events. Assuming $m_{\tilde{g}} = 220\ GeV, m_{\tilde{b}_1} = 160\ GeV/c^2, m_{\tilde{\chi}_1^0} = 60\ GeV/c^2$ in the end 4 and 1 events were observed where 5.6 ± 1.4 and 0.5 ± 0.1 background events were expected for the single resp. double b-taggs. Exclusion plot for the gluino and sbottom masses for the analyzed 38.4 pb^{-1} of data is presented in the Fig.3

5 Search for mGMSB in Diphoton Events with Large Missing E_T

In the minimal Gauge Mediated Supersymmetry Breaking model (mGMSB) [7], the supersymmetry breaks in a hidden sector at a scale $\Lambda \sim 10 - 100\,TeV$, which is much smaller than a GUT scale. Interactions between the new messenger fields in the hidden sector and MSSM particles are mediated by the ordinary gauge fields. Other mGMSB parameters used to describe the model and set here to the following values are messenger mass $M_m = 2\Lambda$, number of messenger fields $N_5 = 1$, the ratio of the vacuum expectation values of the two Higgs fields, $tan\,\beta = 5$ (DØ), resp. 15 (CDF), and the sign of the Higgs mass term $\mu > 0$.

The LSP particle in mGMSB is a very light gravitino ($m_{\tilde{G}} \sim 1\,keV/c^2$) and the model phenomenology is determined by the next-to-lightest SUSY particle (NLSP). For the model points considered here neutralino is the NLSP which decays to γ and LSP. The largest contribution to the cross-section is coming from the second neutralino-first chargino and first chargino pair production: $p\bar{p} \to \chi_2^0\chi_1^{\pm}(\chi_1^+\chi_1^-) \to \chi_1^0\chi_1^0 + X \to \gamma\gamma + 2\tilde{G} + X$. This leads to the final state with 2 photons from the prompt charginos decay and a large missing E_T.

In the DØ analysis, based on 185 pb^{-1} of data, two isolated photons in the central calorimeter $|\eta| < 1.1$ with $E_T > 20\ GeV$ are asked for. All SM backgrounds with true missing E_T involve electrons and not photons, so they are reduced by the matching track veto. Veto on the tracks in the hollow cone $(0.05 - 0.4)$ around the photons directions $\Sigma p_T < 2\ GeV$ and topological cuts $\Delta\phi(mE_T, jet_1) < 2.5$ and $\Delta\phi(mE_T, \gamma) > 0.5$ were designed to get rid of the QCD background, resp. wrong jet energy measurement. Final cut was optimised at $mE_T > 40\ GeV$.

Similar analysis was performed also by the CDF on the 84 pb^{-1} of data, with slightly softer cuts of $E_T > 13\ GeV$ on the central photons $|\eta| < 1.1$ and $mE_T > 25\ GeV$.

No excess of events in the tails of missing E_T distribution above that expected from SM is observed, leading to the conclusion that there is no evidence for mGMSB either in DØ , nor in CDF data. CDF limit on the mass of the lightest chargino is $m_{\chi_1^{\pm}} > 113\ GeV/c^2$. The limits derived by DØ for the breaking scale and the corresponding gaugino masses are $\Lambda > 78.7\ TeV$ resp. $m_{\chi_1^0} > 105\ GeV/c^2$ and $m_{\chi_1^{\pm}} > 180\ GeV/c^2$. They are at that moment the world's best limits.

6 CDF indirect SUSY Search in Rare B-meson Decays

Standard Model prediction for the decay $\mathrm{Br}(B_S^0 \to \mu^+\mu^-) = (3.4 \pm 0.5) \cdot 10^{-9}$ can be enhanced by factors 10-1000 in SUSY at large $tan\,\beta$ [8]. A strong correlation between the muon anomalous magnetic moment a_μ and the branching ratio $Br(B_S \to \mu^+\mu^-)$ in mSUGRA scenarios was also found [9]. This flavour changing neutral current decay was not observed yet and is a very sensitive probe of physics beyond SM.

Data sample of 171 pb^{-1} is based on the low p_T very central $|\eta| < 0.6$ di-muon triggers. Invariant mass of those di-muons has to be in the range $2.7 < M_{\mu^+\mu^-} < 6.0\ GeV/c^2$. Events selection looks for 2 opposite charged muons originating from the common secondary vertex.

Each good muon with $p_T > 2\ GeV$ has to have a matched high quality track with at least 3 hits in the silicon vertex detector. In addition the vector sum of the muons momenta has to satisfy $p_T^{\mu^+\mu^-} > 6\ GeV$. Final search is done in the mass window $\Delta M = \pm 80\ MeV/c^2$ around the world average mass values of $B_S(B_d)$.

One event with a mass $M_{\mu\mu} = 5.295\ GeV/c^2$, falling into both windows was found. There were expected 1.05 ± 0.30, 1.07 ± 0.31 and 1.75 ± 0.34 events in B_S, B_d and combined channels respectively. The derived limit at 90% CL $Br(B_S^0 \to \mu^+\mu^-) < 5.8 \cdot 10^{-7}$ is 3× better than in RunI and the limit $Br(B_d^0 \to \mu^+\mu^-) < 1.5 \cdot 10^{-7}$ is slightly better than limit from BELLE collaboration [10].

7 Summary

No evidence for SUSY particles in up to $185\,pb^{-1}$ of RunII Tevatron data was found. The searches in different channels made possible to set new, higher limits on the masses of sparticles. At the end of year 2004 we expect to have $0.5\,fb^{-1}$ of data (per experiment) on a tape. This will further increase the sensitivity of both experiments beyond the current limits.

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